Small Omni-directional Antenna Development for Mars Sample Return Mission[1][2]

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Abstract— This work addresses the design, analysis and test of omni-directional antennas at 401.5 MHz and 437.1 MHz frequencies, on Mars Orbital Sample (OS) return canisters, which are part of a Mars Sample Return (MSR) mission. The OS in Mars orbit will have a tumbling random orientation. The OS antennas are electrically small (on the order of 0.2 wavelength or less) and linearly polarized. Either a single antenna with two resonant frequencies and a diplexer to provide isolation, or a two-antenna system with a natural isolation of at least 10 dB between the antenna input ports are needed. In this paper results of theoretical and experimental studies on several different types of antennas appropriate to this application are presented. Many of these antennas are designed, fabricated, and tested, and their critical parameters are addressed and investigated. Acceptable near omni-directional pattern coverage and minimum gain levels of better than –2 dB are obtained. These antennas include dual circular patch antennas with slots used to shorten the dimensions, very small square patch antennas with ultra high dielectric ceramic substrates, narrow width patch (ribbon) antennas wrapped around the spherical shell, top-loaded monopoles with different load configurations, and variant PIFA type antennas similar to those used in wireless systems. Many numerical and experimental results are presented and future efforts to further improve the performance are outlined.

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1. INTRODUCTION

The feasibility of a Mars Sample Return (MSR) mission project is presently under investigation by JPL/NASA in conjunction with the French space agency (CNES). In one scenario, it will begin with a launch that will ultimately lead to the delivery of samples from the Red Planet to Earth. Specifically, MSR will employ one or two NASA-provided Landers of nearly identical design and one CNES-provided orbiter carrying a NASA payload of rendezvous sensors, orbital capture mechanisms, and Earth return capsules. The Landers are planned to take surface samples and launch them into Mars orbit in one or more Orbital Sample (OS) canisters.

The OS is composed of a metallic hermetically sealed canister, a UHF transponder, UHF antennas and an array of solar cells all within a spherical shell of about 16 cm in diameter. The electric power is provided by an array of solar cells on the surface of the spherical shell. Near-omni-directional antenna(s) will be located on or near the surface of the OS shell. An orbiter will detect, approach and retrieve the OS using a Radio Direction Finding system (RDF) and a laser ranger (LIDAR) and then deliver it to earth. The canister's solar-powered beacon operates at a frequency of 401.5 MHz. The OS transponder operates at the receive frequency of 437.1 MHz and the beacon transmit frequency of 401.5 MHz, to provide a two-way Doppler ranging and orbit determination.

One of main challenges of the OS development is the design of omni-directional antennas at the 401.5 MHz and 437.1 MHz frequencies. The OS in orbit will have a tumbling random orientation. The OS antennas are linearly polarized, while the RDF antennas on the orbiter are circularly polarized to extract the maximum power subject under the random linear orientation of the OS antenna.

Either a single antenna with two resonant frequencies and a diplexer to provide some isolation, or a two-antenna system with a natural isolation of at least 10 dB between the antenna input ports are needed. Since the antenna dimensions are electrically small (on the order of 0.2 wavelength or less), the issues of impedance match, efficiency and uniformity of the omni-directional patterns become very critical.

In this paper results of theoretical and experimental studies on several different types of antennas appropriate to this application are presented. These antennas include dual circular

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patch antennas with slots used to shorten the dimensions, very small square patch antennas with ultra high dielectric ceramic substrates, narrow width patch (ribbon) antennas wrapped around the spherical shell, top-loaded monopoles with different load configurations, and variant PIFA type antennas similar to those used in wireless systems.

Many of these antennas are designed, fabricated, and tested, and their critical parameters are addressed and investigated. Acceptable near omni-directional pattern coverage and minimum gain levels of better than –2 dB are obtained. In this paper, many numerical and experimental results are presented and future efforts to further improve the performance are outlined.

2. OBJECTIVES AND SPECIFICATIONS

The objectives and the specs of the design are summarized as follows:

Objectives:

Provide omni-directional CW coverage at two frequencies by a single or a number of antennas. Antenna(s) are laid out on or near the surface of a 16-cm diameter dielectric/metallic sphere

Specs:

Frequencies:
-Receive,
437.1000 MHz; Wavelength: 68.63 cm, Bandwidth < 1%
-Transmit,
401.5275 MHz; Wavelength: 74.71 cm, Bandwidth < 1%
Gain: > - 4 dB
Gain variation: +/- 4 dB (desirable)
VSWR: < 2:1 at 50 ohm input.
Antenna input isolation between the two frequencies: > 10 dB (desirable)
Polarization: Linear

Environment:

Antenna is in the following environment. The sphere may or may not be dielectric or metallized. Inside the sphere there is a metallic canister. There are a number of elements including transmitter/receiver, which have metallic parts and are located inside the spherical shell.

There are solar cells on the surface of the sphere with conducting metallic bases and other metallic parts, which cover most of the surface area. Therefore, there is limited space available on the surface to position the antenna(s). Furthermore, the antenna cannot substantially protrude or project above and outside the spherical shell.

Based on the above objectives, requirements, and the environment of operation it is obvious that the antenna dimensions are substantially smaller than 0.2 wavelengths, which is the diameter of the spherical shell. This means designing an electrically small antenna located on a very small metallic sphere.

We may use the same or separate set of antennas for the two frequencies of operation. In that case, bandwidth requirements are minimal. However, the bandwidth for the joint transmit/receive operation is about 8.5%. This may not be feasible for certain type of antennas such as micro-strip patch or slot antennas.

2. ELECTRICALLY SMALL ANTENNAS

The challenges of the electrically small antennas are well understood and documented in the literature. Miniaturized antennas have experienced renewed interest in recent years for wireless and cellular telephony systems. Basically, they have very low radiation resistance causing matching problems and low efficiencies. These problems can be overcome by the use of special matching circuits and/or use very high dielectric constant materials. Our additional challenge may be providing full 4π steradian coverage.

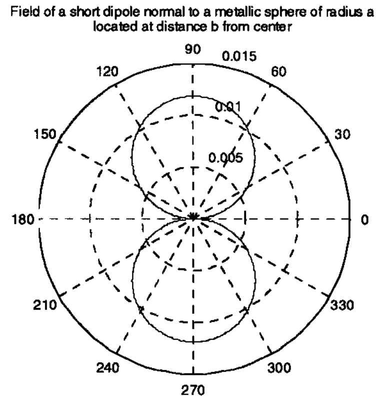
However, they are naturally amenable to producing a more or less omni-directional pattern. Theoretically, of course, there is no solution to the electric vector wave equation, which has a totally omni-directional uniform pattern. There are always null(s) present. However, it is possible to get as close as is realistically possible to an omni pattern in an average sense.

In general two types of antennas can be used for our application. Wire-type antennas and patch type antennas. As far as the wire-type antennas are concerned, loaded monopoles and small loops are the primary candidates. As for the patch type antennas, the use of high dielectric constant materials such as ceramics, in conjunction with clever design techniques become necessary.

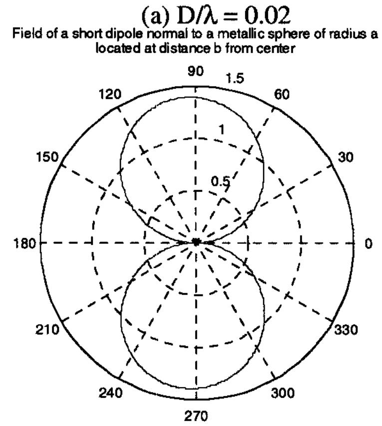
3. ANTENNAS ON A SMALL METALLIC SPHERE

In most ground and wireless applications which require a miniaturized antenna, the coverage is mostly hemispherical with a given ground plane or the earth itself acting as a large ground plane. This application, however, employs the antenna in space for a full spherical coverage but in the presence of a small spherical shell, which may be assumed to work as a ground plane.

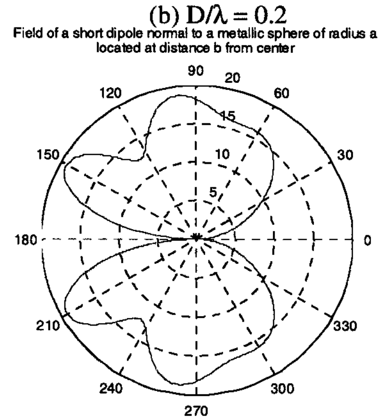
Furthermore, at first blush, it may seem that multiple elements may be required to provide a full 4π coverage. However, our studies based on [1] and similar studies in the literature [2], have shown that due to the electrically small size of the sphere, a single antenna can provide full coverage.



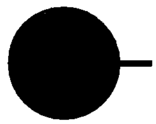
(a) $D/\lambda = 0.02$

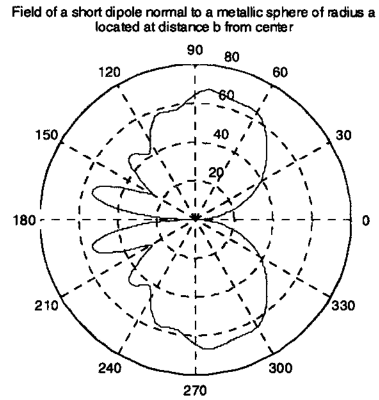


(b) $D/\lambda = 0.2$

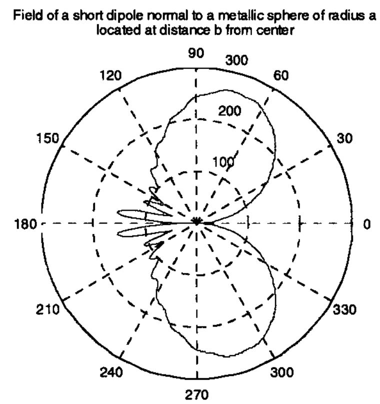


(c) $D/\lambda = 1$

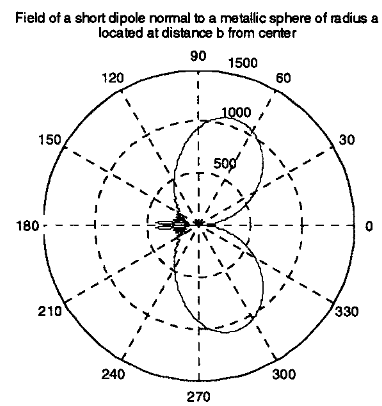




(d) $D/\lambda = 2$



(e) $D/\lambda = 4$



(f) $D/\lambda = 8$

Figures 1(a-f). Computed effect of a spherical conducting shell on radiation pattern of a small dipole

As seen in Figure 1, as the size of the metallic conducting sphere decreases, the effect of the sphere decreases and the pattern of the small dipole approaches that in the free space.

4. HIGH DIELECTRIC SQUARE PATCH ANTENNAS

Standard square patch antennas are typically slightly less than half a wavelength in length and width: L0 ~ 30 cm; W0 ~ 30 cm with air substrate. High dielectric constant substrates are used to reduce the size by the square root of dielectric constant. To further reduce the size a quarter-patch configuration is used which reduces the size by a factor of two as shown in Figure 2, which also broadens the pattern simultaneously. This is due to the fact that the field is zero along a line in the middle of the half-wave patch and can be in effect shorted. And, therefore, half of the patch is removed. The width of the patch does not affect the resonance. It, however, affects the input impedance and the match condition, The width can also be changed, for example, reduced in half to make the patch a square patch. Of course the feed probe position must be adjusted to a new position where the match is achieved. For high dielectric constant materials the feed point is very close to the shorted sidewall and care must be taken in the feed pin soldering.

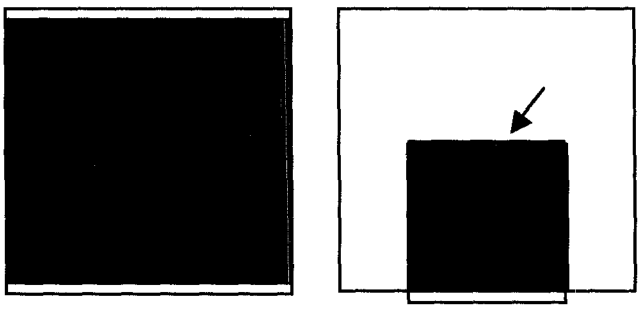


Figure 2. Reduction in size from a half-wave patch to a quarter-wave patch.

Many such patches with various dielectric constant materials and different thicknesses were designed, built, and tested. Some of them are shown in Figure 3. Generally, the efficiency increases with the thickness. Some examples are given below.

Table 1. Square Quarter Patches

	Antenna Patch	Peak Gain
1	0.30"x2.90"x2.90" RT/Duroid 6000, PTFE/Ceramic (e=6.15)	-2.5 dB
2	0.30"x2.20"x2.20" TMM 10i, Thermoset Ceramic loaded plastic (e=9.80)	-3.0 dB
3	0.25"x1.20"x1.20" ECCOSTOCK, HiK500F plastic(e=30)	-5.5 dB
4	0.375"x1.20"x1.20" ECCOSTOCK, HiK500F plastic (e=30)	-1.0 dB

Figure 4. shows a pair of such patches (#4) for the two frequencies of operation. The isolation between these two patches, is however minimal (< 5 dB) and a diplexer is needed to provide further isolation. A typical 3D radiation pattern is shown in Figure 5.

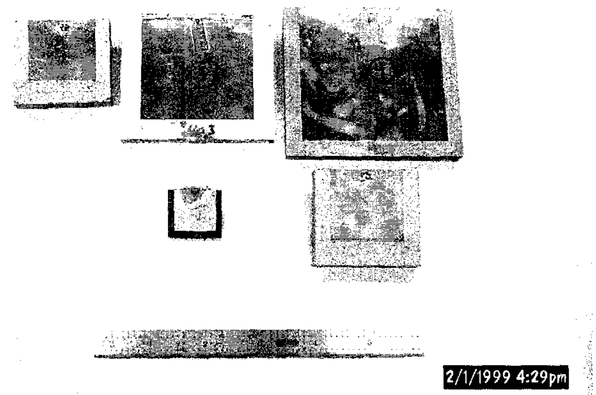


Figure 3. Sample square quarter patches with different thicknesses and dilelectric constants.

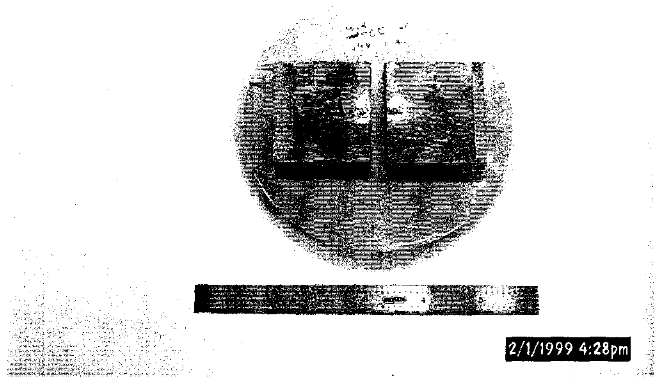


Figure 4. A pair of square quarter patch antennas for operation at 437.1 and 401.5 MHz frequencies. Case 4 in Table 1.

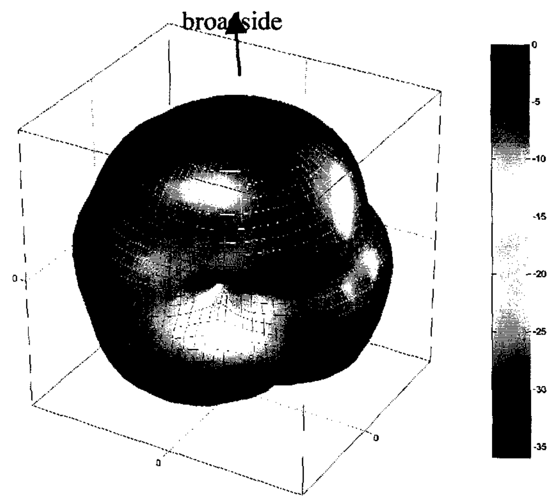


Figure 5. A 3D surface plot of the 437-MHz quarter patch radiation pattern normalized to peak

5. STICK OR RIBBON PATCH ANTENNAS

By reducing the width of the quarter-wave patch even further than the square quarter patch, a stick or ribbon configuration is obtained. This configuration is in essence very similar to the so-called inverted-F and PIFA antennas [3-4]. Table 2. shows some example cases of the ribbon patch or stick antennas. Figure 6 shows a sample of ribbon patch antennas.

Table 2. Ribbon Quarter Patches

	Antenna Patch	Peak Gain
1	0.30"x0.75"x3.00" RT/Duroid 6000, PTFE/Ceramic (e=6.15)	-3.5 dB
2	0.25"x0.60"x4.30" TMM 3, Thermoset Ceramic loaded plastic (e=3.27)	-3.0 dB
3	0.25"x0.80"x4.30" TMM 3, Thermoset Ceramic loaded plastic (e=3.27)	-2.5 dB

This configuration is most suitable for wrapping around the equatorial region of the spherical shell as shown in Figure 7. This figure shows a mock up of the OS sphere together with a circular patch antenna which will be described shortly.

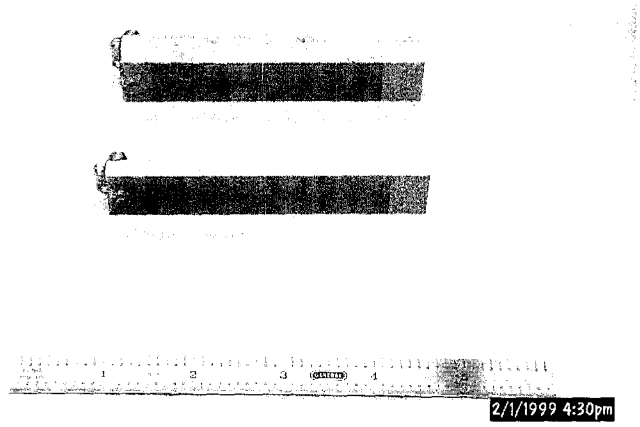


Figure 6. A pair of stick patch antennas for operation at 437.1 and 401.5 MHz frequencies. Case 3 in Table 2.

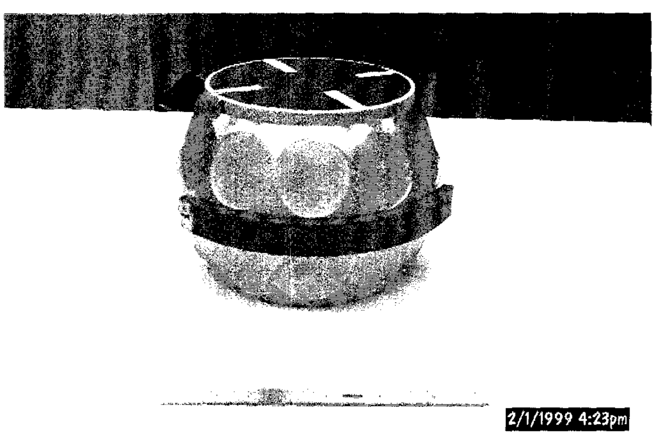


Figure 7. A curved ribbon patch antenna on the mock-up of the OS sphere

6. WRAP-AROUND PATCH ANTENNAS

Yet another variation of the quarter patch antenna was studied in which a substantial portion of the surface of the sphere is used to make two back to back quarter patches for the transmit and receive frequencies as shown in Figure. These patch do not require high dielectric constant substrates and hence should be more efficient than those patches.

However, there are a number of difficulties that need to be overcome. One is the design difficulty, since patchs are not flat but doubly curved. In addition the antenna is integrated in the body of the sphere and its ground plane may interfere with the transmitter/receiver electronics inside the outer layer of the sphere. Also in this configuration the solar cells must be placed on the patch surface and care must be taken that the radiating slots of the patches are not blocked by these cells and do not interfere with radiation and the impedance match of the patches.

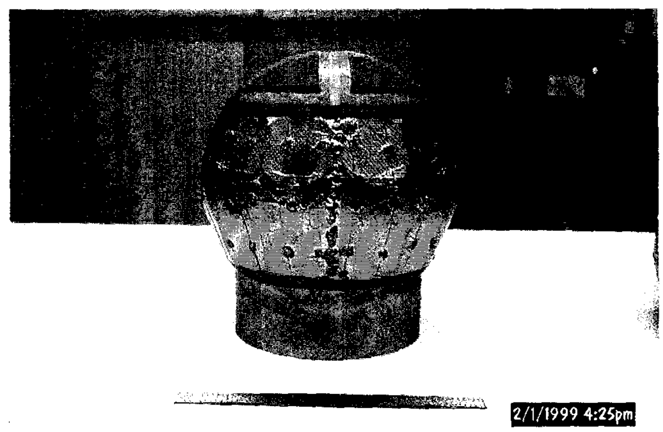


Figure 8. Wrap-around quarter patch antennas on the surface of OS canister mock-up

7. SLOTTED CIRCULAR PATCH ANTENNAS

A better performance was achieved by a specially designed circular microstrip patch. This design uses high dielectric-constant substrate material as well as multiple slots on the patch in order to reduce the size requirements of the design. Both techniques have been previously employed separately by other researchers [7-8]. This antenna combines these two techniques with dual-frequency and dual-polarization capabilities. In general, this antenna radiates a nearly omni-directional pattern with good efficiency and cross-pol characteristics. With two slots located on a circular patch, as shown in Fig. 9, the current on the patch or the field underneath the patch will resonate from one edge of the patch and take longer path around the slots to reach the opposite edge. This longer path, in essence, reduces the resonant frequency or the physical dimension of the antenna.

The antenna as sketched in Fig. 9, is a dual-linearly-polarized circular patch with two feed probes and two pairs of different-length slots. One feed probe that sees the pair of shorter slots generates the higher frequency field at 437.1 MHz, while the other feed probe with the pair of longer slots resonates at the lower frequency of 401.5 MHz.

Although the two linearly polarized fields are orthogonal to each other, the spacecraft's CP antenna will see the two orthogonal fields from the canister antenna with equal quality. In addition, this antenna, due to its dual orthogonal feed probes, provides a very high isolation (> 20 dB) between the two feed ports.

The substrate used in this antenna is Rogers TMM material with a relative dielectric constant of 9.8. A shorting pin is placed at the center of the patch to suppress undesirable modes and, hence, to provide good port isolation and to lower cross-pol radiation. A photo of the antenna mounted on the OS canister is given in Fig. 10. This Figure also shows the mock-up solar cells on the surface of the OS canister.

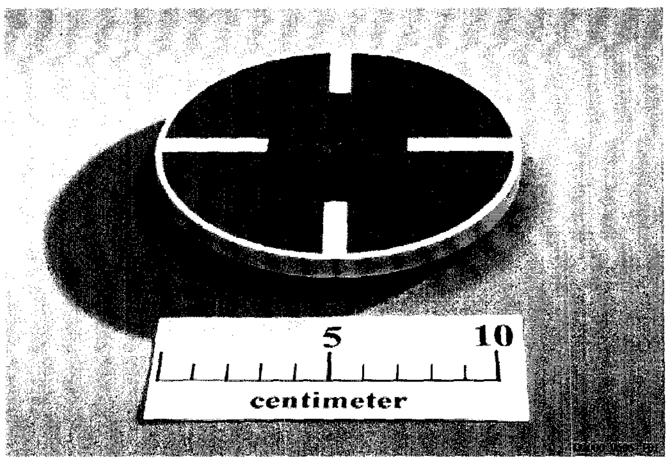


Figure 9. Dual linearly polarized slotted circular patch antenna

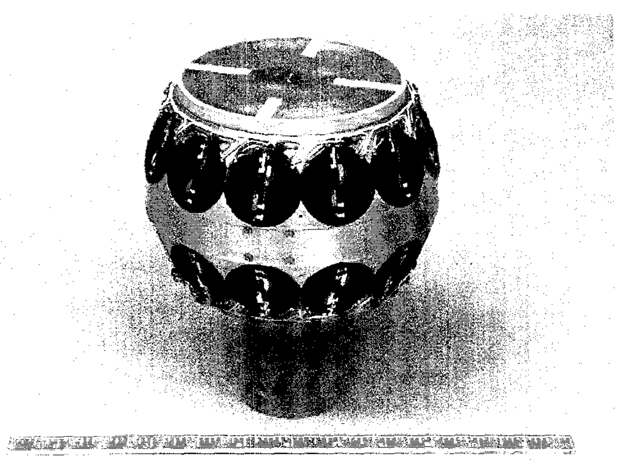


Figure 10. Picture of the mock-up canister with the circular patch antenna and the solar cells

The measured 3D plot of the circular slotted patch antenna when mounted on the OS canister mock-up is given in Fig. 11(a and b). In the E-plane, the antenna radiates a nearly omni-directional pattern. In the H-plane, two nulls are formed in the direction containing the plane of the antenna. The antenna achieved a peak gain of 1.0 dB, while the integrated directivity of this 3-D pattern is 1.8 dB. This indicates an antenna efficiency of 83%, which is rather good for a miniaturized antenna. The antenna, due to its extreme small size, achieved very narrow bandwidth. The measured 2:1 VSWR bandwidths are 1.2 MHz at 401.5 MHz and 1.4 MHz at 437.1 MHz, which indicate a percentage bandwidth of about 0.3%.

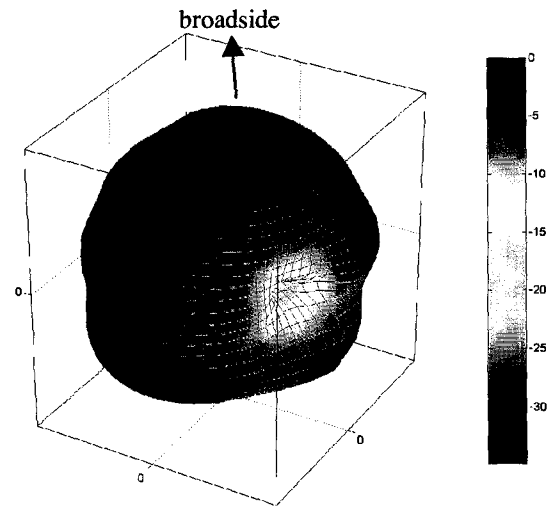


Figure 11(a) A 3D measured pattern of the slotted circular patch antenna on the OS mock-up. 60°-from-broadside view of V-port at 401 MHz

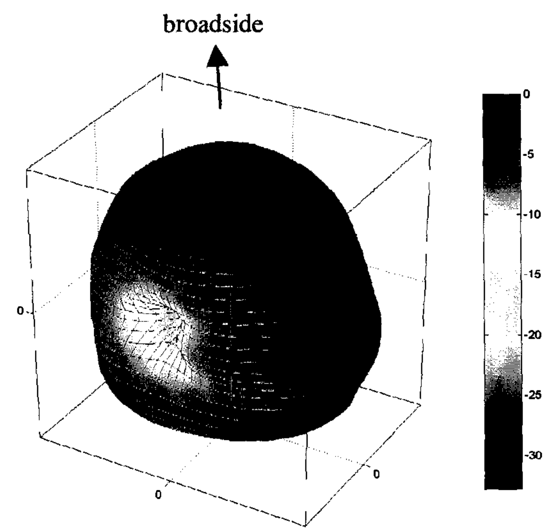


Figure 11(b) A 3D measured pattern of the slotted circular patch antenna on the OS mock-up. 60°-to-broadside view of H-port at 437 MHz

8. Loaded Monopoles and S-Patch Antennas

The square and circular patches discussed so far, both need to be located at a cut-off section of the pole of the OS sphere. They are not conformal to the surface of the sphere. These antennas will be covered by a hard foam radome to fill the cut-off region. The weight is a major consideration particularly for the circular patch, due to the relatively large size and thickness of the patch and the heavy dielectric material.

Wire-type antennas can provide a lightweight alternative. A simple monopole sticking out of the spherical shell to a height of about 18 cm was built and tested on the shell. It provided very good performance and wide bandwidth covering both transmit and receive bands. However, this simple antenna violates the conformality requirement. One choice is a half-wave Hula-Hoop antenna [6]. An acceptable alternative would be a top-loaded short monopole. The probe is located at the same ground level as that of the square and circular patch base plate and is extended to the surface of sphere where the top loading occurs. This is done by simply extending metal strips on the surface of the foam substrate or filler.

Figure 12 shows some examples of this design. The name S- or Z-patch is due to the shape of the top loading branches. This design is very lightweight and conformal to sphere ans provides very good performance. The problem so far has been the required bandwidth of 8.5% for transmit/receive operations and the inability to provide any kind of isolation. However, promising steps are being made.

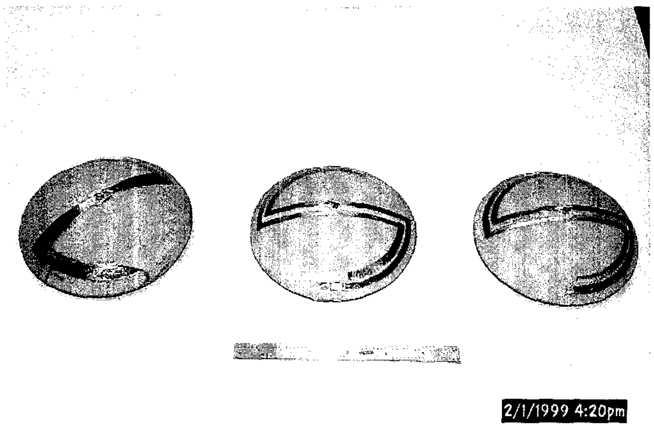


Figure 12 Sample top-loaded monopoles: S and Z-patch antennas

9. Test Results

All the tests were performed in lab and on the antenna range at JPL. VSWR and pattern measurements are relatively difficult for low gain antenna at these low UHF frequencies. The radiation from the connecting feed cable as well as from the support boom on the antenna range can contaminate the pattern measurements. Figure 13 shows the set-up at the JPL MESA antenna range. In an ideal situation, the antenna and OS canister should be in free space with no support structures and cables in the vicinity. There are plans for modifying the range and providing the signal from inside the OS without any outside cable and support boom. However, with precautions taken so far, the presented results should be fairly accurate.

Another concern, particularly in the case of the high dielectric substrate patch antennas, is the narrow resonance bandwidth, which may possibly drift out of the transceiver's frequency range due to the large temperature variation in Mars orbit (-80° C to +60° C) and the concomitant change in the dielectric constant as well as material expansion and contraction. A temperature chamber test was performed on the circular patch antenna of Figure 9 with the result given in Table 3. Surprisingly, the antenna showed relatively good temperature stability. This is attributed primarily to the temperature stable nature of the substrate material (Rogers TMM).

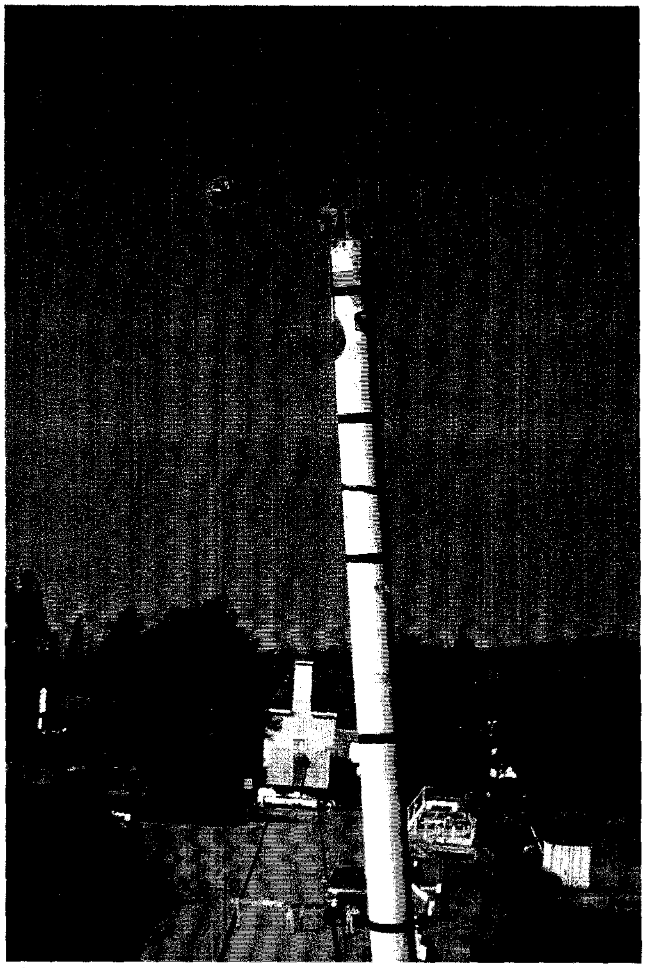


Figure 13. Antenna range set-up with the OS canister at the end of the boom

Table 3. Antenna temperature test results

Temp °C	Port #1 Frequency /Return loss, dB	Port #2 frequency / Return loss
+60	401.5 MHz / -15.8 dB	437.2 MHz / -18.6 dB
+40	401.5 MHz / -16.1 dB	437.1 MHz / -18.7 dB
+23	401.5 MHz / -18.0 dB	437.1 MHz / -18.6 dB
-20	401.5 MHz / -27.2 dB	437.1 MHz / -24.1 dB
-40	401.5 MHz / -35.7 dB	437.0 MHz / -28.2 dB
-60	401.4 MHz / -31.7 dB	437.0 MHz / -31.0 dB
-80	401.4 MHz / -43.5 dB	437.0 MHz / -36.0 dB

10. Summary and Conclusions

A major effort was conducted to obtain a miniaturized UHF antenna for a future Mars Orbital Sample return canister. Many antennas were theoretically and experimentally investigated with some good and promising results. Some of them radiate a nearly omni-directional pattern with good efficiency and good cross-pol characteristics.

Monopoles, loaded monopoles, miniaturized ceramic substrate square, strip as well as circular patch antennas were developed. At this juncture the orthogonally-fed single circular slotted patch provides the best RF performance at the expense of a heavy weight. The substrate material used is very temperature stable and meets the challenge of surviving the large temperature variation in Mars orbit.

The ribbon patches can be made conformal and lighter but need further efficiency optimization and extension to dual frequency operation. Loaded monopoles on the other hand are very light and provide excellent performance at a single frequency. Work needs to be done to extend its performance to dual frequency operation. True uncontaminated pattern measurements are very difficult and efforts need to be made to improve them.

Acknowledgment

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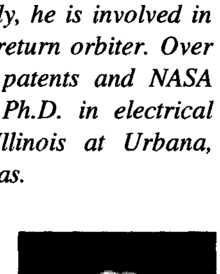

John Huang *is with the Jet Propulsion Laboratory, California Institute of Technology. He received his B.S.E.E. degree from the Michigan Technology University, Houghton, MI in 1969, M.S.E.E. degree from University of California, Berkeley in 1970, and Ph.D. degree from the Ohio State University, Columbus in 1978. He worked for six years since 1970 at the Naval Weapons Center, China Lake, California, and 20 years at the Jet Propulsion Laboratory. With over 25 years of technical experience, he has made* *significant contributions to the design of printed antennas and phased arrays for mobile and satellite communications. He is currently leading the development of inflatable array antennas. Dr. Huang, a Fellow of IEEE and a principal engineer at JPL, has published over 100 journal articles and conference papers, and has contributed to several book chapters. He is currently an IEEE Distinguished Lecturer and has been invited to speak at various institutes domestically, as well as internationally. He has also been invited to serve on a number of symposium committees and chaired a number of symposium sessions. Over the course of his career, Dr. Huang has designed numerous mobile and satellite antennas, pioneered the development of several microstrip antenna concepts, received four US patents, and received more than fifteen NASA certificates of recognition.*

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